INTRODUCTION

Excess body weight is recognized as a fundamental cause of numerous health issues. In addition to assessing weight, the concept of “overfat” or “normal-weight obesity” has emerged, referring to individuals with excessive body fat despite falling within the normal weight range. Surprisingly, a significant proportion of individuals with normal weight, ranging from 20% to 40%, may fall into the category of overfat. While there is a consensus that improving dietary habits and physical activity patterns is crucial for reducing body fat, debates continue regarding the optimal quantity and type of exercise and ideal dietary strategies. Among the various dietary methods proposed for fat reduction, the ketogenic diet (KD) has recently gained popularity. The KD is characterized by low carbohydrate, moderate protein, and high fat intake, with daily energy intake distribution approximately as follows: carbohydrates (5%), protein (20%), and fat (75%).

In a conventional diet, our bodies mainly utilize carbohydrates and fats as primary energy sources. However, when following the KD, a significant metabolic shift occurs. The body transitions from relying on carbohydrates to using fats as the primary energy source, achieved by depleting carbohydrate stores. The central nervous system, specifically the brain, typically relies on glucose as its primary energy source owing to the exclusive utilization of glucose by the blood-brain barrier. Consequently, glucose is the primary fuel for the brain.

Debates regarding the potential risks associated with the KD center on the brain. After a few days on the KD, one of the brain’s primary energy sources, glycogen, becomes depleted. This depletion can lead to stress and other issues. However, proponents of the KD argue that despite the need for an adaptation period, this dietary approach induces a state of ketosis. During ketosis, as fats are broken down, three types of ketone bodies are produced: acetoacetate, β-Hydroxybutyrate, and acetone. These ketone bodies increase within the body, allowing the brain, heart, muscles, and other tissues to use them as an energy source (Figure 1). These metabolic adaptations have been suggested to promote fat oxidation, leading to favorable body fat level changes, and potentially affecting muscle mass and exercise performance by influencing fuel utilization and metabolic efficiency.
Nevertheless, the effects of the KD on body fat, muscle mass, and exercise performance remain a topic of ongoing debate, with conflicting results reported in the literature. Therefore, this review examines the effects of the KD in areas where its potential benefits have been proposed and provides a brief overview of the evidence.

**EFFECTS OF THE KETOGENIC DIET ON BODY FAT**

Several studies have demonstrated the positive effects of the KD on body composition across various age groups and clinical conditions. For instance, a study comparing the KD with a hypocaloric diet in children and adolescents with obesity found that the KD was more effective in terms of weight loss and improvement in metabolic parameters. This study suggests that the KD can be a viable and safe alternative for weight loss in children and adolescents.

In another study conducted by Goss et al., older adults with obesity maintained their calorie intake at normal levels over 8 weeks, and a comparison was made between the KD and a low-fat diet. The results indicated that the KD group exhibited a greater reduction in total fat mass than the low-fat diet group. Notably, the KD group experienced a threefold greater decrease in visceral adipose tissue. Consequently, this study suggests that weight loss through the KD, particularly in reducing visceral adipose tissue, which is strongly associated with metabolic and functional outcomes, may offer greater benefits for older adults than weight loss through a low-fat diet.

Hussain et al. compared the effects of a 24-week low-calorie diet and the KD in individuals with type 2 diabetes. The KD was more effective than the low-calorie diet in significantly reducing body weight, body mass index (BMI), and waist circumference (WC). Additionally, the KD group demonstrated favorable effects on blood glucose levels and alterations in hemoglobin and glycosylated hemoglobin, total cholesterol, low-density lipoprotein cholesterol (LDL), high-density lipoprotein cholesterol (HDL), and triglyceride (TG) levels. Some participants also experienced a 50% reduction or discontinuation of their initial dosage of antidiabetic medication.

Evidence regarding the effects of the KD on weight management is compelling; however, the underlying mechanisms of its action remain unclear. Paoli et al. based on existing studies, presented evidence for the effectiveness of the KD in weight loss as follows: 1) suppression of appetite through the satiety effect of protein and resulting changes in the appetite hormone ghrelin levels, 2) reduced lipogenesis and increased fat oxidation, 3) enhanced metabolic efficiency in fat metabolism due to a decreased respiratory quotient, and 4) increased energy expenditure due to the thermic effect of protein and gluconeogenesis.

Regarding the fourth piece of evidence, Ludwig et al. analyzed the impact of the KD on total energy expenditure (TEE). They investigated the differences in effects based on the duration of application. A meta-analysis of 29 studies, found that the KD initially leads to a temporary decrease in TEE; however, after approximately 2.5 weeks, a more significant increase in TEE was observed. During this adaptation period, individuals may experience symptoms of “Keto Flu,” including headaches, brain fog, fatigue, irritability, nausea, sleep disturbances, and constipation. This study provides partial insights into the mechanisms through which the KD promotes weight loss and the minimum adaptation period required to achieve the effects of the KD.

Available evidence suggests that the KD potentially exerts a favorable influence on body fat reduction. Nevertheless, it remains imperative to meticulously consider individual variability in the response and long-term effects on body fat. From a long-term perspective, the success of a
The impact of ketogenic diet

**Table 1. The key aspects and findings of the references.**

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KD: ketogenic diet; HIIT: high intensity interval training; TEE: total energy expenditure

nutritional approach is determined by the extent of weight regain\(^{14}\). In this regard, there are limited data on the effect of the KD on weight loss or reduction in body fat\(^{15,16}\).

Diet and exercise play vital roles in reducing overweight status. High-intensity interval training (HIIT) has gained popularity as an efficient exercise strategy for improving cardiovascular endurance, enhancing heart metabolism, and positively affecting body composition changes\(^{17-19}\). Cipryan et al.\(^{20}\) investigated the independent and interactive effects of the KD and HIIT on visceral fat reduction. The KD and KD+HIIT groups showed significant decreases in visceral fat, whereas the HIIT group showed minimal effects. Based solely on these findings, it can be concluded that the KD may be more effective for reducing visceral fat than HIIT alone without dietary intervention.

However, it is important to consider that this comparison focuses solely on changes in visceral fat and excludes other potential benefits of HIIT, such as cardiorespiratory fitness and cardiovascular health improvements. Nonetheless, the KD appears to be more effective in reducing visceral and overall body fat than exercise alone without dietary intervention. This is a potentially beneficial approach, particularly for individuals with limited engagement in physical activity.

**EFFECTS OF THE KETOGENIC DIET ON MUSCLE MASS**

As described in the preceding section, the KD is an effective strategy to reduce body weight and body fat. Another important aspect to consider is the potential effect of the KD on muscle mass. If the KD leads to a reduction in muscle mass and body fat, its applicability is limited for athletes and the general population.

Several studies have suggested that carbohydrate restriction in the KD may contribute to reduced muscle mass. The potential mechanisms through which the KD could negatively affect muscle mass are elucidated based on relevant literature as follows: 1) reduction in glycogen storage, which could impact muscle performance and recovery\(^{21}\); 2) inadequate intake of essential proteins crucial for muscle composition, maintenance, and recovery\(^{22,23}\); 3) changes in muscle energy availability because of the shift towards fat metabolism\(^{24}\); 4) impaired protein synthesis attributed to decreased insulin levels\(^{15}\).

Interestingly, the combination of the KD and exercise did not prevent a reduction in muscle mass\(^{8,25}\). Some studies have indicated that during the period of KD application, exercise leads to increased utilization of muscle amino acids for gluconeogenesis due to glycogen depletion in the liver and muscles. This utilization could also be attributed to sodium and water excretion and body water loss due to glycogen depletion\(^{8}\). However, Cipryan et al.\(^{20}\) pointed out that during the initial 4 weeks of the 12-week KD experimental period, there was a noticeable decline in participants’ muscle mass, which subsequently stabilized. They explained this as a transient phenomenon resulting from the initial reduction in total energy intake and changes in the carbohydrate proportion during the early stages of the KD intervention.

Conversely, numerous studies positively evaluate the KD’s impact on muscle mass. The proposed mechanisms are as follows: 1) muscle protein synthesis stimulation through activation of the mammalian target of rapamycin pathway\(^{26}\); 2) muscle protein breakdown reduction by suppressing the ubiquitin-proteasome system\(^{27}\); 3) increased secretion of growth hormone that plays a vital role in muscle growth and repair, promoting protein synthesis and inhibiting protein breakdown\(^{28}\); 4) nutrient uptake acceleration into muscle cells because of improved insulin sensitivity\(^{29,30}\); 5) promotion of muscle recovery, repair and growth through anti-inflammatory effects\(^{31,32}\), and glycogen preservation within muscles owing to increased fat oxidation.

Wilson et al.\(^{33}\) compared the KD and a conventional diet over 11 weeks and found that both groups showed similar levels of muscle hypertrophy and increased strength. One noteworthy aspect of this study was that the participants were experienced in resistance training, and the KD group showed a remarkable increase in testosterone, a key factor in muscle synthesis, compared with the conventional diet group. Nonetheless, the current research results suggest that it is more appropriate to view the KD as a strategy for selectively removing fat without muscle loss rather than a strategy for muscle hypertrophy.

The impact of the KD on muscle mass is still under discussion; however, it is believed to be influenced by key
factors such as total energy and protein intake. To maximize muscle hypertrophy through the KD, daily total energy intake needs to be optimized. For maximal muscle hypertrophy, a caloric surplus is recommended, meaning that the daily total energy intake should exceed the total daily energy expenditure by 5%.

During periods of muscle hypertrophy, minimizing unnecessary fat gain by not exceeding a weekly weight gain of 0.25-0.5% of one’s body weight is essential. Furthermore, excessive protein intake can induce gluconeogenesis and disrupt the state of ketosis, so protein consumption should be optimized. Consuming up to 2.1g/kg/day of protein allows for the maintaining a state of ketosis.

**EFFECTS OF THE KETOGENIC DIET ON EXERCISE PERFORMANCE**

Research related to the KD has primarily been conducted in the context of weight or fat reduction. Investigations into the relationship between the KD and exercise performance are lacking. The KD may positively impact exercise performance by providing benefits related to metabolic regulation, ketone body production, mitochondrial function enhancement, inflammation reduction, and weight loss.

The benefits of the KD in relation to exercise performance have been explored primarily in the context of endurance performance. Nonetheless, conflicting results exist in the data, and more studies have report that the KD provides no benefits or even impairs performance in athletes.

A study by Burke et al. involved elite world-class race walkers who alternated between a typical high-carbohydrate diet and the KD for 3 weeks each while undergoing intensified training. This study observed significant improvements in peak aerobic capacity and whole-body fat oxidation at various speeds and intensities when following the KD. However, this study highlights that the KD impacted exercise economy during the real-life race performance of elite endurance athletes. In other words, after adopting the KD, race walkers required increased oxygen consumption to maintain the same exercise workload or speed, indicating reduced efficiency. This reduction in the exercise economy ultimately negated the benefits of intensified training. Therefore, if exercise economy is impaired owing to the KD, it becomes challenging for race walkers to expect improvements in their performance.

Pathak and Baar explained the decrease in high-intensity exercise performance due to the KD. The key muscle adaptation resulting from the KD and the activation of peroxisome proliferator-activated receptor (PPAR) enhances muscle fat oxidation but can also contribute to a reduction in high-intensity exercise performance. When PPAR is activated, it promotes the expression of genes related to fat oxidation and energy production. While this adaptation can benefit endurance activities requiring sustained energy over longer durations, it is less efficient at intensities greater than 65% of VO2max. Endurance athletes on a KD ultimately require more oxygen to maintain the same exercise workload or speed as athletes on a conventional diet during high-intensity performance. This PPAR-driven shift in energy substrate utilization may lead to reduced performance during demanding endurance activities that require intense energy bursts.

Furthermore, there have been concerns about the potential health risks associated with athletes adopting the KD. One such study by Volek et al. investigated the metabolic characteristics of 10 long-distance runners who followed a KD for over 6 months. The results indicated that runners experienced decreased body weight and body fat compared with their pre-KD state. However, the blood concentration of ketone bodies, a metabolic byproduct, significantly increased, leading to side effects such as fatigue, insomnia, and digestive issues in athletes. These findings suggest that adopting an extremely low-carbohydrate high-fat diet, such as the KD, may pose potential health risks to individuals engaged in long-distance exercise.

In contrast, some studies have reported improvements in high-intensity endurance performance. McSwiney et al. investigated the KD in endurance athletes over 12 weeks and conducted various performance tests, including a 100 km timed trial, a 6-second sprint, and a critical power test. The results showed that compared with athletes following a conventional diet, there was no significant difference in the 100 km timed trial performance after adapting to the KD. However, the KD-adapted athletes consistently demonstrated in-
Increased fat oxidation rates during exercise. In the 6-second sprint conducted immediately after the 100 km timed trial to simulate the sprint finish in endurance races and the critical power test, athletes following the KD exhibited improved performance.

Although there is insufficient information available on the effects of the KD on anaerobic exercise, studies have suggested that the KD may have a negative impact on anaerobic exercise. These negative effects include the following: 1) impaired ability for glycolysis, which is necessary for short-term high-intensity anaerobic exercise; 2) limitation in glycogen utilization leading to early fatigue and reduced performance during exercise; 3) limited availability of creatine phosphate regeneration, which impacts the rate of ATP regeneration required for explosive exercise; 4) decreased glycogen and insulin secretion leading to increased protein breakdown resulting in muscle mass reduction; 5) electrolyte loss and dehydration due to reduced carbohydrate intake resulting in muscle cramps, reduced muscle function, and impaired performance during anaerobic activities.

Nevertheless, a study by Paoli et al. targeted elite gymnasts and implemented the KD for 1 month without altering their training routines. The results revealed a reduction in body fat and maintenance of strength. Furthermore, Kephart et al. analyzed the impact of the KD over 3 months on exercise performance and body composition in CrossFit trainees. No significant differences in strength or muscle mass between the KD and control groups were observed. Similarly, Sawyer et al. focused on men and women who strength-trained and investigated the effects of a 7-day short-term KD on strength and power. The findings indicated that despite reductions in body weight, both sexes sustained strength and power. This provides a rationale for the KD in the domains of strength and power.

Despite the ongoing debate surrounding the impact of the KD on exercise performance, it appears that the KD can be particularly beneficial for athletes involved in weight-category sports and those in whom aesthetic appearance plays a crucial role in their performance. The KD has the potential to preserve muscle mass regardless of the type of exercise and supports the reduction of body fat, making it a robust approach.

Paoli et al. focused on natural bodybuilders over 8 weeks with equal total energy and protein intake conditions: one group followed the KD, whereas the other adhered to a conventional diet. The results indicated that the KD group significantly reduced body fat more than the conventional diet group. The conventional diet group showed a slight increase in muscle mass, whereas the KD group maintained their existing muscle mass without experiencing muscle loss. Moreover, insulin sensitivity, a critical metabolic health marker, significantly improved only in the KD group. On the other hand, inflammatory cytokines (IL-1, IL-6, TNF-a) increased in the conventional diet group but decreased in the KD group compared with baseline. Therefore, implementing the KD during a phase focused on maximizing fat reduction can serve as a strategy not only for efficient fat loss without muscle loss but also for preventing potential metabolic and immune health decline during the body fat reduction phase. For these reasons, the KD can provide advantages to athletes with weight category restrictions and individuals aiming to reduce fat while preserving muscle mass.

The potential of the KD to improve exercise performance remains a topic of debate. In summary, the KD can enhance endurance performance by boosting fat oxidation; however, it may lead to a performance decline in high-intensity activities that rely heavily on glycogen. To effectively utilize the KD to enhance exercise performance, it is crucial to consider factors such as individual characteristics, duration of dietary adaptation, training level, and the type of exercises performed.

Table 3. The key aspects and findings of the references.

<table>
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<td>Elite race walkers</td>
<td>High carbohydrate vs. KD diets during intensified training</td>
<td>Improved peak aerobic capacity and fat oxidation during KD but reduced exercise economy during real-life race performance</td>
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<td>Elite runner</td>
<td>Explains KD’s impact on high-intensity exercise performance</td>
<td>Submaximal exercise performance (&lt;60% VO2max) may improve in runners, but at high exercise intensities (approximately &gt;65% VO2max), the efficient transport of fatty acids to the mitochondria is limited, resulting in a negative impact on performance.</td>
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<td>Endurance athletes</td>
<td>KD applied for 12 weeks to endurance athletes in various performance tests</td>
<td>No significant difference in a 100km time trial performance, but KD-adapted athletes consistently exhibited higher fat oxidation rates and improved performance in high-intensity sprint and critical power tests.</td>
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<td>Long-distance runners</td>
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KD: ketogenic diet; VO2max: maximal oxygen consumption
CONCLUSION

The KD, which restricts carbohydrate intake and emphasizes the consumption of fat and proteins, can potentially affect body fat, muscle mass, and exercise performance. Despite evidence supporting these claims, challenges remain in establishing clear guidelines for its application. Future research should prioritize optimizing the application of the KD in diverse populations, elucidating its underlying mechanisms, and validating its long-term effects on sustainability and safety.

REFERENCES

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